SEASONAL HYDRODYNAMIC CONTROLS AND MULTIVARIATE POLLUTION SIGNATURES IN IKWU STREAM, A TROPICAL COMMUNITY WATER-SUPPLY SOURCE IN SOUTHEASTERN NIGERIA

***Eboh, S.[1], Ezugwu, C. N.[2], Mmonwuba N. C.[3], Eze, E. E.[4], Ije, I.[5]**

[1,4,5]Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike, Umuahia, Nigeria.
[2]Department of Civil Engineering, Alex Ekwueme Federal University of Ndufu-Alike, Ikwo LGA, Abakaliki, Nigeria.
[3]Department of Civil Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli Campus, Awka, Nigeria

*Corresponding Author: eboh.solomon@mouau.edu.ng

ABSTRACT

Small tropical streams used for community water supply experience simultaneous dilution, sediment mobilisation and oxygen-balance responses during seasonal transitions. This study quantified dry- and wet-season hydrodynamic and physicochemical variation along four reaches of Ikwu Stream in southeastern Nigeria and evaluated the resulting source-water implications. A structured longitudinal design generated 72 matched observations across Umu-Ire, Umuegwu-Okpuala, Umukabia and Amaogwugwu. Width, depth, velocity, discharge, temperature, pH, dissolved oxygen (DO) and electrical conductivity were measured in situ; turbidity, colour, total dissolved solids, total suspended solids (TSS), total solids, alkalinity and five-day biochemical oxygen demand (BOD_5) were determined using standard water-analysis procedures. Seasonal effects were evaluated with paired $\log_2$ response ratios and bootstrap confidence intervals. Pearson relationships were examined after adjustment for season, reach, lateral position and downstream distance, and principal component analysis (PCA) was used to resolve process signatures. Mean discharge increased from 0.817 to 2.251 m^3/s in the wet season, DO increased by 12.8%, and BOD_5 decreased by 14.2%; however, TSS increased by 61.1% and turbidity remained above 5 NTU in most observations. Adjusted associations identified coupled discharge-TSS, turbidity-TSS and alkalinity-BOD_5 signals, while PCA separated a hydrodynamic suspended-solids axis from an organic-mineral axis. Umu-Ire exhibited the lowest BOD_5 and remained the most defensible reach for detailed abstraction assessment; however, this physicochemical ranking does not establish microbial safety or suitability for untreated consumption, and treatment must address persistent particulate loading and unmeasured microbial risk. The results demonstrate that increased wet-season flow does not uniformly improve source-water quality and support season-specific monitoring, source protection and multi-barrier treatment.

Keywords: Ikwu Stream; seasonal hydrodynamics; surface-water quality; Pearson correlation; principal component analysis; suspended solids; rural water supply

1.0 INTRODUCTION

Access to reliable raw water is a prerequisite for safe and resilient water-supply systems. In many rural and peri-urban settings, perennial streams remain the most accessible sources because groundwater development is technically difficult, spatially unreliable or economically prohibitive. Yet the engineering usefulness of a stream cannot be inferred from flow permanence alone. A source may yield adequate water while simultaneously carrying suspended solids, biodegradable organic matter, ionic constituents and microbial hazards that vary sharply with rainfall, land use and local waste-disposal practices. Contemporary drinking-water guidance therefore treats source selection, catchment protection, treatment and operational surveillance as connected barriers rather than independent decisions (World Health Organization, 2022, 2024).

Seasonality is especially important in small tropical catchments. During low flow, reduced dilution and longer residence time can intensify the influence of domestic discharges, livestock access, washing activities and other point or near-point sources. During the wet season, higher discharge can dilute some dissolved and oxygen-demanding constituents, but rainfall-runoff connectivity can mobilise eroded soil, faecal material, nutrients and organic debris. Consequently, dissolved oxygen may improve because of lower temperature, turbulence and reaeration even while turbidity, suspended solids or microbial risk deteriorate. Global evidence shows that hydroclimatic extremes alter water quality through several interacting pathways, including concentration, dilution, transport, resuspension and changes in biogeochemical processing (UNESCO World Water Assessment Programme, 2024; van Vliet *et al*., 2023). Recent tropical studies similarly report that the transition from dry to wet conditions expands hydrological connectivity and changes the sources and transport of dissolved and particulate material (Alkhadher *et al*., 2025; Gobana *et al*., 2025; Justin *et al*., 2026; Norouzi *et al*., 2024).

This dual response has direct consequences for water-treatment design. High turbidity and TSS increase the burden on coagulation, flocculation, clarification and filtration, can shield microorganisms from disinfection and may cause rapid filter head-loss. Conversely, high BOD_5 and depressed DO signal organic loading and possible sanitary stress, while electrical conductivity, TDS and alkalinity help distinguish dilution from mineral or effluent-related influences and broader land-use or salinisation pressures (Giri & Qiu, 2016; Kaushal *et al*., 2018). No single parameter therefore provides a sufficient source-water diagnosis. The engineering question is not simply whether the wet season is "better" or "worse", but which processes dominate under each hydrological condition and how those processes should change abstraction, treatment and monitoring decisions (American Public Health Association *et al*., 2023; World Health Organization, 2022, 2024).

Multivariate analysis offers a useful framework for resolving these interactions, provided that statistical associations are interpreted in relation to sampling design and field context. Pearson correlation can identify linear co-variation among hydraulic and water-quality variables, but pooled correlations may be confounded by season, reach or downstream position. Principal component analysis (PCA) can reduce a correlated parameter set to a smaller number of process-oriented axes, but the axes remain descriptive and must be interpreted with hydrological and sanitary evidence. Recent studies in southern Nigeria and other tropical systems demonstrate the value of combining seasonal sampling with multivariate methods to identify hydrochemical, sediment and anthropogenic signatures (Alkhadher *et al*., 2025; Gobana *et al*., 2025; He *et al*., 2024; Justin *et al*., 2026; Lu *et al*., 2024; Nnorom *et al*., 2019; Norouzi *et al*., 2024; Ubuoh *et al*., 2024). Older foundational studies remain relevant for the statistical principles, but contemporary datasets emphasise the need to separate seasonal effects from within-reach associations (Kannel et al., 2007; Koklu et al., 2010; Legendre & Legendre, 2012; Montgomery & Runger, 2018; Ogwueleka, 2015; Shrestha & Kazama, 2007; Singh *et al*., 2004).

Ikwu Stream is located in the Afugiri area of Umuahia North Local Government Area, Abia State, southeastern Nigeria. Communities along the stream use it for domestic collection and livelihood activities, particularly when alternative supplies are inadequate. The catchment includes source-proximal reaches, high-use bridge and confluence zones, reaches influenced by community and institutional activity, and a wider downstream reach where transport, dilution and partial self-purification can occur. Potential pressures include washing, bank disturbance, agricultural runoff, livestock activity, poorly controlled wastewater pathways, fish-farming return flows and abattoir-related wastes. These pressures are relevant because they can introduce biodegradable organic matter, suspended solids, nutrients and sanitary hazards into a stream being considered for community water supply.

Previous assessments of comparable streams have often reported parameter concentrations and compliance status without explicitly connecting hydrodynamics, seasonal contrasts, longitudinal behaviour and multivariate process interpretation to abstraction decisions. For Ikwu Stream, the practical gap is therefore not the absence of measurements alone, but the absence of a compact and reproducible evidence chain showing how measured flow and water quality interact across season and reach. A robust source-water paper should distinguish descriptive pooled patterns from relationships that persist after adjustment for the sampling design; it should also state the limits of inference where seasonal campaigns are not replicated across multiple years.

The present study addresses that gap using a 72-observation dry/wet dataset from four monitoring reaches. The objectives were to: (i) quantify seasonal changes in stream hydraulics and physicochemical quality; (ii) identify reach-scale and longitudinal source-water contrasts; (iii) estimate matched seasonal effect sizes using $\log_2$ response ratios; (iv) evaluate Pearson associations after adjustment for season, reach, lateral position and downstream distance; (v) resolve dominant multivariate signatures with PCA; and (vi) translate the findings into abstraction, treatment and monitoring implications. The central hypothesis was that wet-season flow would improve oxygen condition and reduce some dissolved or organic indicators, but would simultaneously increase suspended-solids transport. The study contributes a reproducible, design-aware interpretation of a small tropical stream and provides an evidence base for subsequent microbial monitoring, pilot treatment testing and detailed intake design.

2.0 MATERIALS AND METHODS

2.1 Study design and setting

The investigation used a quantitative field-monitoring and laboratory-analysis design with matched dry- and wet-season observations. The analytical unit was a single season-reach-distance-position record. Four reaches were selected to represent a progression from source-proximal conditions through high-use and pollution-impact zones to a wider downstream reach. The design was intended to capture spatial heterogeneity within each reach while preserving a common structure that allowed records to be paired between seasons.

The study area lies within the humid tropical environment of Ohuhu, Umuahia North Local Government Area, Abia State, southeastern Nigeria, where rainfall controls stream stage, catchment connectivity and the transport of suspended and dissolved material. The research programme commenced in early 2025 and covered representative dry- and wet-season conditions during the 2025 hydrological cycle. The monitored Ikwu Stream corridor extends approximately from 5.5700° to 5.6061° N and from 7.4497° to 7.4813° E in the World Geodetic System 1984 (WGS 84). Four reaches were established at Umu-Ire, Umuegwu-Okpuala, Umukabia and Amaogwugwu to represent source-proximal, high-use, pollution-impact and downstream transport conditions, respectively. Representative reach coordinates and analytical roles are presented in Table 1.

Table 1 Monitoring reaches, representative WGS 84 coordinates and analytical roles

Reach and representative coordinates (WGS 84)	**Field setting**	**Analytical role**
Umu-Ire 5.5700° N, 7.4790° E	Source-proximal reach near Amaenyi-Ikwu confluence	Upstream reference and prospective low-burden source-water reach
Umuegwu-Okpuala 5.5800° N, 7.4813° E	Bridge/confluence reach near Nkata-Ikwu	High domestic-use and washing-activity reach
Umukabia 5.6061° N, 7.4603° E	Iyi-Ogwe-Ikwu confluence reach	Pollution-impact and organic-loading assessment
Amaogwugwu 5.5931° N, 7.4497° E	Downstream reach near Egweze-Ikwu confluence	Transport, dilution and partial self-purification assessment

2.2 Materials, instruments and analytical scope

The field and laboratory programme required clean water-sampling bottles, 300-mL BOD bottles with ground-glass stoppers, a cool box with ice packs, labels and waterproof field sheets; a measuring tape or calibrated range measure for channel width; a graduated wading rod for depth; the velocity-measurement apparatus documented in the contemporaneous field record; and portable meters for temperature, pH, DO and electrical conductivity. Laboratory work required a nephelometric turbidity instrument, colour-comparison or spectrophotometric equipment, a calibrated balance, filtration apparatus, pre-weighed filter media or evaporating dishes, drying ovens, titration glassware and standard reagents for alkalinity and BOD_5 analysis. Analytical-grade reagents and deionised water were used for standards, blanks and rinsing.

Table 2 links each measured variable to the operational method used in the study. Field and laboratory procedures followed the relevant method families in Standard Methods for the Examination of Water and Wastewater (American Public Health Association, American Water Works Association, & Water Environment Federation, 2023). Instrument calibration, blank checks, stabilised readings, gravimetric mass checks and titrant standardisation were incorporated into the analytical workflow.

Table 2 Materials, measurement procedures and output units

Variable/material	**Measurement or analytical procedure**	**Output/quality control**
Channel width and depth	Width measured across the active channel; depth measured at representative verticals with a graduated rod	m; repeated readings and field-note check
Velocity and discharge	Representative velocity obtained with the recorded field method; discharge calculated by the velocity-area relation	m/s and m^3/s; equation and unit check
Temperature	Calibrated field thermometer or temperature probe measured in situ	°C; stabilised reading
pH	Portable pH meter, calibrated with at least two buffers bracketing expected values	pH units; calibration before use

Variable/material	Measurement or analytical procedure	Output/quality control
Dissolved oxygen	Portable DO meter measured in situ, with Winkler verification where available	mg/L; zero/span or air-saturation check
Electrical conductivity	Portable conductivity meter measured in situ	µS/cm; standard-solution check
Turbidity and colour	Nephelometric turbidity method; Pt-Co colour comparison or spectrophotometric method	NTU and Pt-Co units; blanks/standards
TDS, TSS and TS	Gravimetric determination by filtration, evaporation and drying to constant mass	mg/L; pre-weighed media/dishes and balance check
Alkalinity	Acid titration to the prescribed endpoint	mg/L as $CaCO_3$; titrant standardisation
BOD_5	Initial/final DO difference after 5 d dark incubation at 20 °C, with dilution correction where required	mg/L; air-free bottles, blank/dilution-water check

2.3 Sampling framework and field protocol

Field campaigns were conducted under representative dry- and wet-season conditions during 2025. Within each reach, nine longitudinal sub-points were established at 0, 100, 200, 300, 400, 500, 600, 700 and 800 m. The field sequence alternated right-bank, centreline and left-bank positions so that the dataset retained lateral variation without treating the three positions as triplicate samples at the same distance. The same reach-distance-position keys were used in both seasons, producing 36 records per season and 72 complete records overall (4 reaches × 9 sub-points × 2 seasons). At each sub-point, the team first recorded field conditions, including visible sediment, debris, foam, colour, odour, bank disturbance, washing activity and other potential pollution pathways. Unstable variables-temperature, pH, DO and conductivity-were then measured in situ after the probes had equilibrated. Channel width, representative depth and velocity were recorded before water samples were collected. The longitudinal arrangement and data-flow sequence are shown in Figure 1.

Representative flow velocity was measured in situ at each sub-point using the field velocity-measurement procedure adopted for the campaign. The recorded velocity was combined with active channel width and mean depth in the velocity-area relation to estimate discharge. Repeated readings and field-note checks were used to minimise measurement and transcription errors.

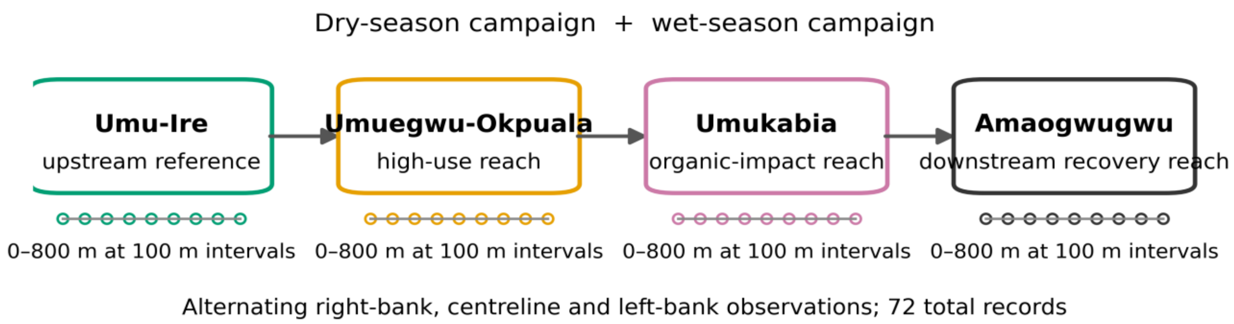

Figure 1: Longitudinal sampling framework used for the dry- and wet-season campaigns

2.4 Hydraulic measurements and derived discharge

Channel cross-section was represented by the measured active width and mean depth at each record. For the simplified field approximation used in the dataset, cross-sectional area A was calculated as the product of width B and mean depth y. Discharge Q was then obtained from the continuity relation using representative mean velocity V (Chow, 1959):

$$A = By \quad (1)$$

$$Q = AV = ByV \quad (2)$$

All quantities were converted to SI units before calculation. Width and depth were recorded in metres, velocity in metres per second and discharge in cubic metres per second. A spreadsheet and Python check recalculated Q from B, y and V and compared the result with the recorded discharge. Values were screened for impossible signs, obvious decimal shifts and discontinuities with adjacent longitudinal observations. Because channel area was represented by the product of active width and mean depth, the discharge values were interpreted as reach-comparative estimates rather than as a site-specific stage-discharge rating curve.

2.5 Sample collection, preservation and laboratory analysis

After completion of in-situ measurements, grab samples were collected in clean, labelled containers from flowing water while avoiding surface films and bottom disturbance. Containers were rinsed with sample water when compatible with the intended analysis. BOD_5 samples were collected directly into BOD bottles without headspace or entrained bubbles. Samples not analysed immediately were placed in an ice-cooled box, protected from light and transported to the laboratory as soon as practicable. The chain of custody linked each bottle to season, reach, distance and lateral position.

Turbidity was determined nephelometrically and reported in nephelometric turbidity units. Apparent/true colour was determined against the platinum-cobalt scale. TSS was obtained by filtering a known sample volume through pre-weighed media, drying the retained residue to constant mass and dividing the mass increase by sample volume. TDS was determined from the filtrate by evaporation and drying, while total solids were determined from an unfiltered aliquot. Gravimetric concentrations were expressed in milligrams per litre. Alkalinity was measured by titration with standard acid to the prescribed endpoint and reported as milligrams per litre as $CaCO_3$ (American Public Health Association et al., 2023).

BOD_5 was measured from the difference between initial DO and DO after five days of dark incubation at 20 °C. For an undiluted sample, BOD_5 was calculated as:

$$BOD_5 = DO_0 - DO_5 \quad (3)$$

When dilution was required, the oxygen depletion was divided by P, the decimal fraction of sample in the incubated bottle:

$$BOD_5 = (DO_0 - DO_5)/P \quad (4)$$

Field DO was retained as the stream-condition measurement, whereas the DO values used in the BOD test represented laboratory oxygen depletion. The analytical dataset included turbidity, colour, TDS, TSS, TS, alkalinity and BOD_5 for every field record.

2.6 Quality assurance and quality control

Quality control began with unambiguous sample identification and immediate recording of field observations. Portable meters were inspected and calibrated before deployment using appropriate standards. Probes were rinsed between records and readings were accepted only after stabilisation. Glassware, filtration equipment and sample containers were cleaned before use; BOD bottles were filled without bubbles and incubated in darkness. Where duplicate or verification measurements were available, they were compared before data entry. Laboratory quality checks included reagent blanks or deionised-water checks, calibration standards for instrumental methods, verification of balance performance, titrant standardisation and inspection of gravimetric mass stability. Data-entry checks required TDS, TSS and TS to be non-negative and physically coherent; the recorded TS values were compared with the corresponding dissolved and suspended fractions. Units were standardised before analysis, and formulas were independently reproduced in Python.

No value was deleted merely because it was high or low. A record would be excluded only if field or laboratory documentation identified instrument failure, sample loss, impossible units or transcription error. The final dataset contained no missing values in the variables analysed.

2.7 Data management and statistical analysis

The master dataset was stored in tidy format with one row per season-reach-distance-position record. Numeric columns were width, depth, velocity, discharge, temperature, pH, DO, conductivity, turbidity, colour, TDS, TSS, TS, alkalinity and BOD_5; categorical columns were season, reach and lateral position. Records were sorted by season, reach and downstream distance. No imputation was performed. Descriptive summaries used the arithmetic mean and sample standard deviation (dof = 1) for each season and for each reach-season combination.

Matched seasonal effects were calculated after pivoting the dataset by reach, distance and position. For each positive-valued variable, the record-level response ratio was $\log_2$(wet/dry). The reported effect was the mean of the 36 matched $\log_2$ ratios. Non-parametric 95% confidence intervals were obtained from 5,000 bootstrap resamples of the matched records using a fixed random seed of 20260719. Positive values indicate higher wet-season measurements; a value of 1 indicates a twofold increase and -1 a halving. These intervals quantify uncertainty across the sampled spatial records and do not represent interannual climatic uncertainty because only one campaign per season was available.

Raw Pearson coefficients were used only as descriptive overlays in Figures. 7 and 8. To reduce confounding by the structured design, adjusted relationships were calculated in two steps. First, each continuous variable was regressed by ordinary least squares on an intercept, season, reach, lateral position and standardised downstream distance. Categorical predictors were dummy coded with one reference level removed. Second, Pearson coefficients were calculated between the residuals of each variable pair. For $m = 36$ unique pairwise tests among nine variables, two-sided p values were adjusted using the Benjamini-Hochberg false-discovery-rate procedure (Benjamini & Hochberg, 1995). The residual correlations describe within-design co-variation; they do not establish causality.

PCA was performed on discharge, temperature, pH, DO, conductivity, turbidity, TSS, alkalinity and BOD_5. TDS and total solids were excluded from the PCA because they were mathematically or operationally redundant with solids-related variables and could overweight the same process. Each retained variable was centred and scaled using the full-dataset mean and population standard deviation (ddof = 0). Singular-value decomposition produced scores, loadings and explained-variance ratios. Component signs were oriented only to make the graphical interpretation consistent; sign reversal does not change the PCA solution (Legendre & Legendre, 2012; Montgomery & Runger, 2018).

Analyses were implemented in Python 3.10 or later with pandas for data handling, NumPy for numerical operations, SciPy for correlation and distribution calculations, and Matplotlib for figures. The reproducibility script regenerates the seasonal summaries, bootstrap effects, adjusted correlations, PCA scores and loadings, and all 12 figures from Supplementary Data S1, subject only to minor platform-dependent differences in font rendering.

2.8 Methodological scope and inferential limits

The sampling sub-points provide spatial resolution but are nested within four reaches and two seasonal campaigns. They are therefore not equivalent to 72 independent seasonal replicates. The analyses are designed to characterise the observed campaigns, compare matched spatial records and identify process-consistent signals. Claims about year-to-year variability, extreme-storm behaviour or long-term trends require repeated campaigns across at least one complete hydrological year. Likewise, the study does not establish potable-water compliance because microbial and several chemical hazards were outside the analytical scope. These limits are incorporated into the interpretation below rather than treated as reasons to disregard the observed hydraulic and physicochemical patterns.

3.0 RESULTS AND DISCUSSION

3.1 Seasonal hydrodynamic response and source-water meaning

Wet-season discharge increased throughout the monitored system. The overall mean rose from 0.817 ± 0.437 m³/s in the dry campaign to 2.251 ± 0.931 m³/s in the wet campaign, an increase of 175.6% (Table 3). The shift was produced by wider/deeper flow and higher recorded velocities across the reaches (Figure 2). The magnitude of the change confirms that season is a first-order control on water availability, transport capacity and treatment-plant intake conditions.

The physicochemical response was not uniformly beneficial. Mean temperature decreased from 29.06 to 27.23 °C, DO increased from 4.95 to 5.58 mg/L and BOD_5 decreased from 5.38 to 4.62 mg/L. These changes are consistent with cooler water, stronger turbulence, increased reaeration and dilution of biodegradable organic matter. Similar increases in DO and decreases in some dissolved or oxygen-demanding indicators have been observed where wet-season flow dilutes point-source influence (Alkhadher *et al*., 2025; Gobana *et al*., 2025). However, the same rainfall-runoff connectivity can introduce sediment, organic debris and microorganisms; therefore, improved DO and reduced BOD_5 cannot be interpreted as proof of microbial safety or suitability for untreated drinking-water use (Justin *et al*., 2026; World Health Organization, 2022, 2024).

TSS increased from 18.31 to 29.49 mg/L (61.1%), while turbidity increased from 6.26 to 6.68 NTU. Thus, the wet season improved oxygen condition while increasing particulate loading. The distribution plots in Figure 3 show that discharge and TSS underwent the clearest upward shifts, whereas conductivity and BOD_5 moved downward. This competing response is hydrologically plausible: higher flow expands catchment connectivity and stream power, increases bank and bed mobilisation, and carries fine material that may not settle before reaching a proposed intake (Alkhadher *et al*., 2025; Lu *et al.,* 2024; Norouzi *et al*., 2024; van Vliet *et al.,* 2023). For treatment design, the implication is that wet-season raw water may require more robust coagulation, solids removal and filter management even when DO appears favourable.

Table 3 Overall seasonal summary for principal variables (n = 36 observations per season)

Variable	Dry season mean ± SD	Wet season mean ± SD	Change
Discharge (m³/s)	0.817 ± 0.437	2.251 ± 0.931	+175.6%
Temperature (°C)	29.056 ± 0.870	27.225 ± 0.535	-6.3%
DO (mg/L)	4.950 ± 0.572	5.583 ± 0.424	+12.8%
Conductivity (µS/cm)	190.736 ± 30.244	179.458 ± 29.191	-5.9%

Variable	Dry season mean ± SD	Wet season mean ± SD	Change
Turbidity (NTU)	6.261 ± 0.520	6.681 ± 1.058	+6.7%
TSS (mg/L)	18.306 ± 4.740	29.489 ± 8.140	+61.1%
Alkalinity (mg/L as $CaCO_3$)	73.528 ± 15.710	70.972 ± 15.529	-3.5%
BOD_5 (mg/L)	5.378 ± 1.586	4.617 ± 1.388	-14.2%

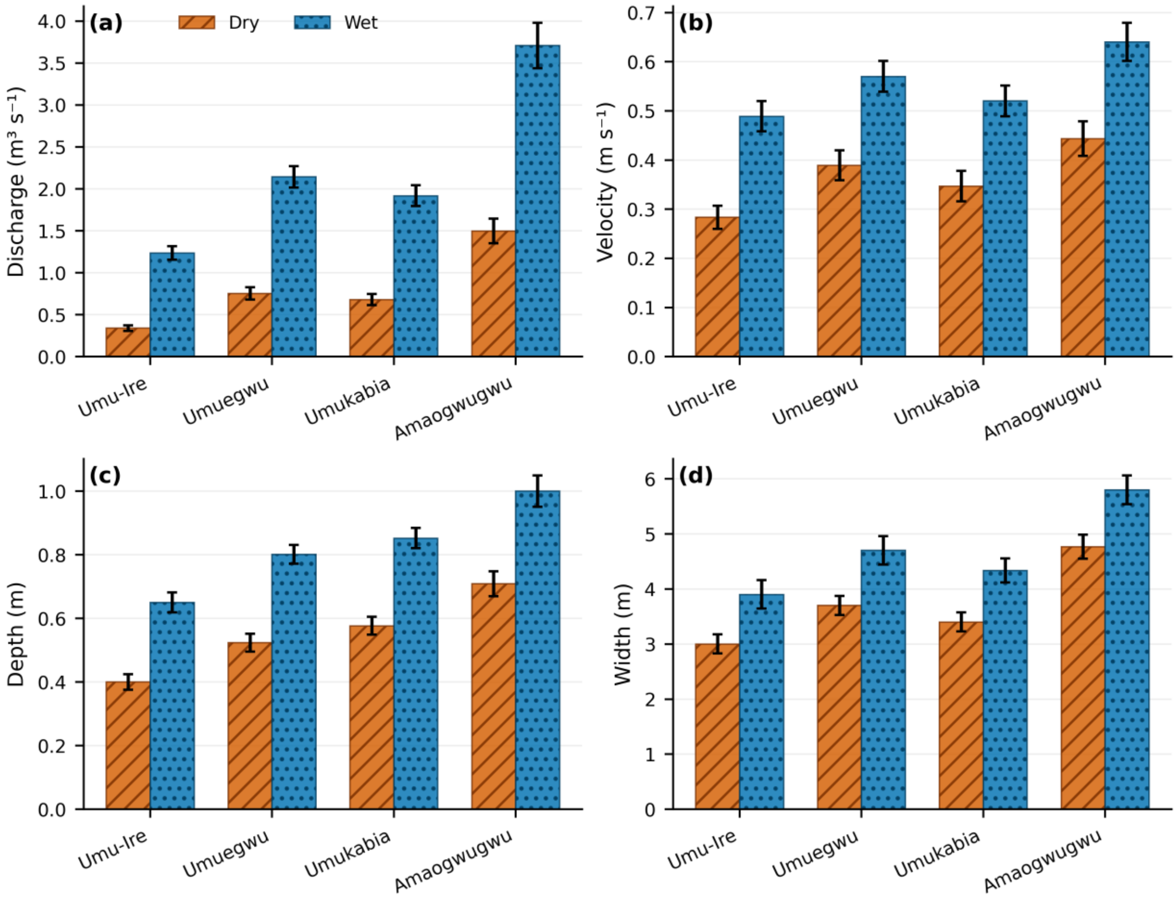

Figure 2: Reach-scale seasonal means of discharge, velocity, depth and width; error bars represent standard deviations across nine longitudinal sub-points

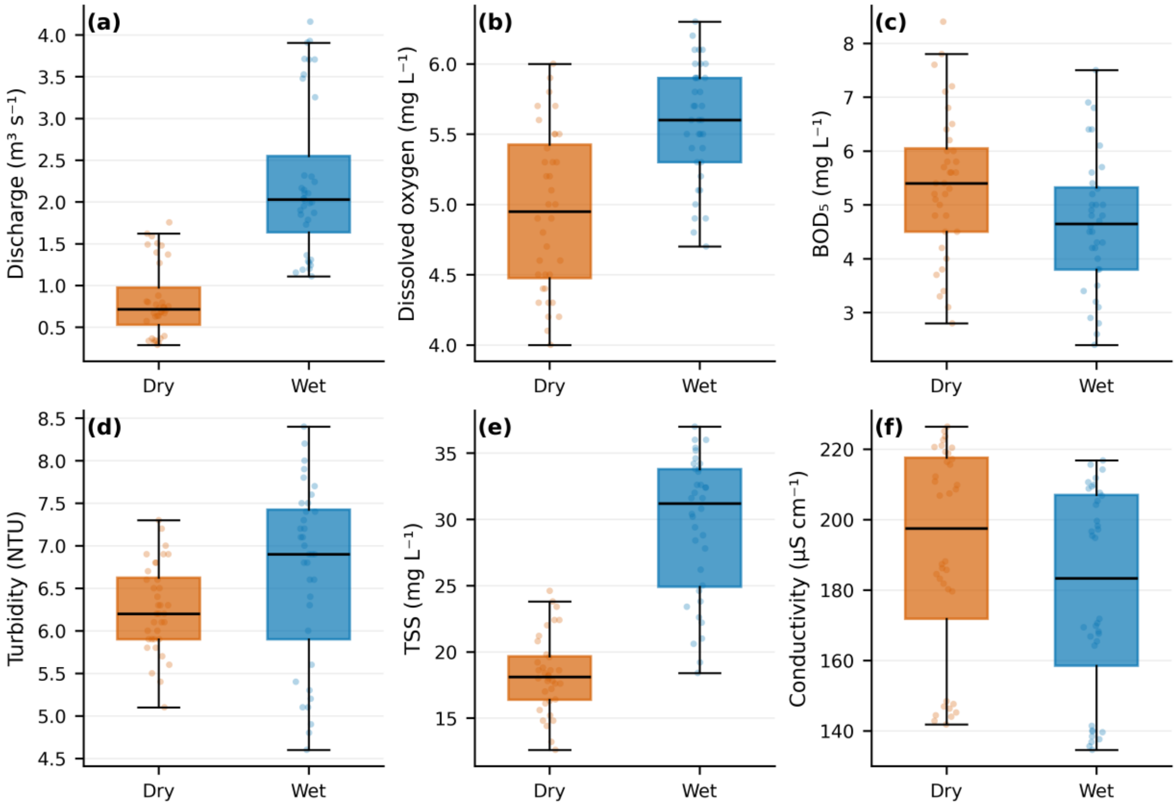

Figure 3: Seasonal distributions of discharge, dissolved oxygen, BOD_5, turbidity, TSS and conductivity; points show individual observations

3.2 Reach-scale and longitudinal contrasts

Reach-scale means revealed a stable contrast between lower-burden and higher-impact areas (Table 4; Figure 4). Umu-Ire had the lowest mean BOD_5 in both seasons (3.64 and 3.08 mg/L), which supports its role as the upstream reference and preferred reach for further abstraction assessment. This preference is based only on the measured physicochemical indicators; low BOD_5 does not demonstrate the absence of E. coli, total coliforms or other microbial hazards. Umukabia had the highest BOD_5 in both campaigns (7.00 and 6.14 mg/L), consistent with its selection as an organic-loading impact reach. Amaogwugwu carried the greatest discharge but did not achieve the lowest BOD_5 or highest DO, indicating that downstream dilution and turbulence did not fully erase cumulative upstream influence.

The wet-season increase in discharge was visible at every distance in every reach (Figure 5), demonstrating that the hydraulic response was system-wide rather than driven by a single anomalous station. DO and BOD_5 profiles in Figure 6 show local longitudinal fluctuations superimposed on the reach-scale pattern. These fluctuations are expected in small streams where aeration, depth, local inflows, bed condition and nearby activities vary over short distances. The profiles should therefore be interpreted as a source-water screening transect rather than a fully calibrated oxygen-sag curve (Chapra, 1997).

Turbidity exceeded 5 NTU in 69 of 72 observations. The threshold is used here as an operational treatment indicator, not as a complete compliance decision. The near-universal exceedance means that even the preferred upstream reach requires clarification and filtration before disinfection. National and international guidance emphasises that turbidity control is integral to effective disinfection and that source-water assessment must also include microbial hazards (Standards Organisation of Nigeria, 2015; World Health Organization, 2022, 2024). The current physicochemical results cannot exclude faecal contamination, particularly during wet-weather runoff; recent tropical evidence shows that favourable aggregate water-quality classifications can coexist with substantial wet-season faecal contamination (Justin *et al*., 2026).

Table 4 Reach-scale seasonal means for key source-water indicators

Season	Reach	Q (m^3/s)	DO (mg/L)	BOD_5 (mg/L)	Turbidity (NTU)
Dry	Umu-Ire	0.339	4.63	3.64	5.81
Dry	Umuegwu-Okpuala	0.752	5.48	5.68	6.86
Dry	Umukabia	0.679	5.40	7.00	6.33
Dry	Amaogwugwu	1.497	4.29	5.19	6.04
Wet	Umu-Ire	1.236	5.63	3.08	5.11
Wet	Umuegwu-Okpuala	2.295	5.88	4.69	6.74
Wet	Umukabia	1.689	5.76	6.14	7.63
Wet	Amaogwugwu	3.784	5.06	4.56	7.24

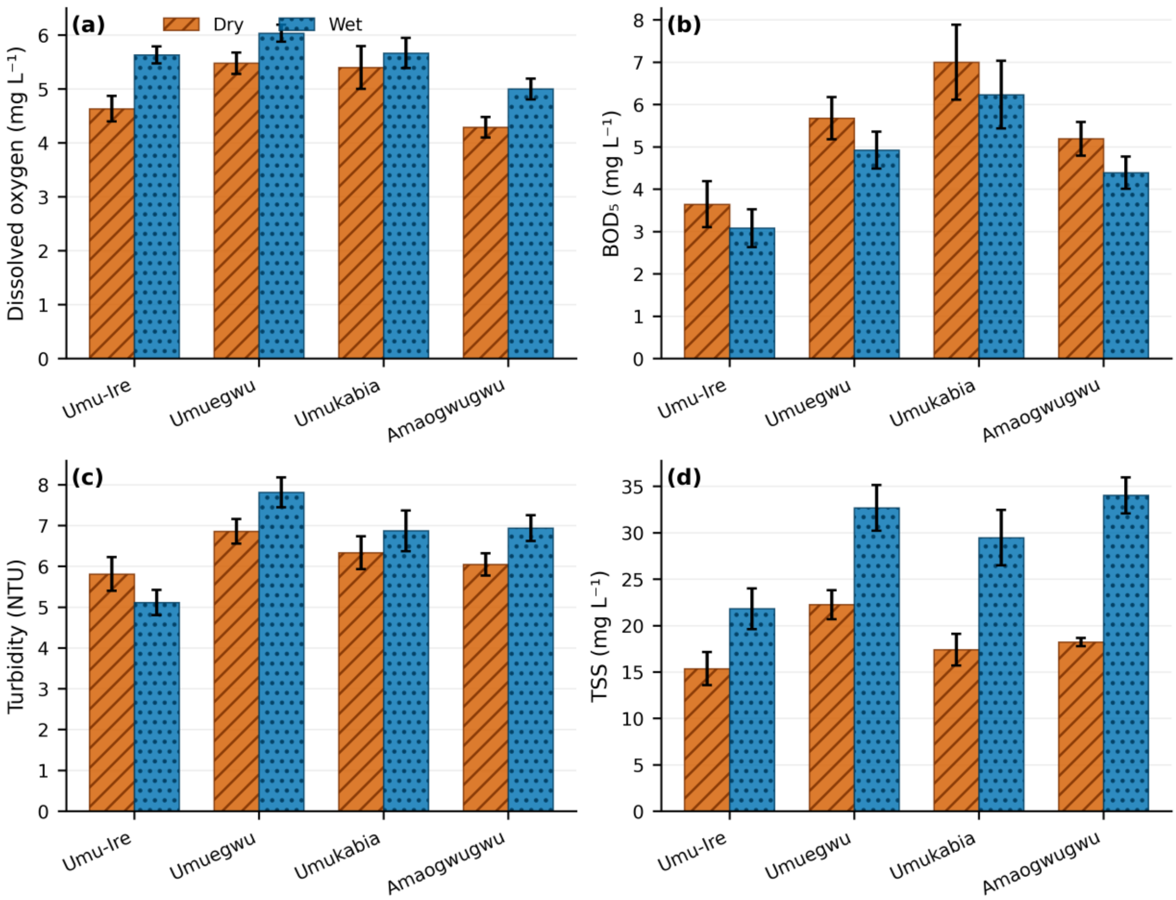

Figure 4: Reach-scale seasonal means of dissolved oxygen, BOD_5, turbidity and TSS; error bars represent standard deviations across nine longitudinal sub-points

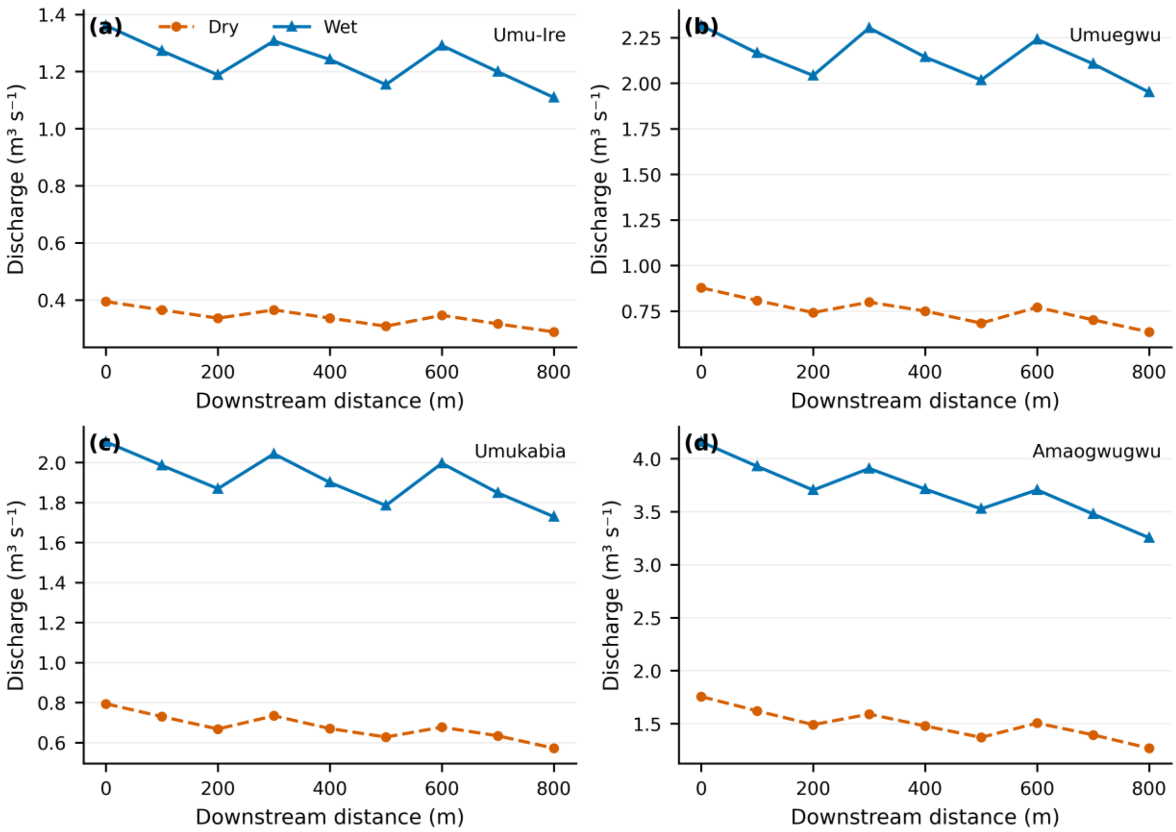

Figure 5: Longitudinal discharge profiles for each monitoring reach during the dry and wet campaigns

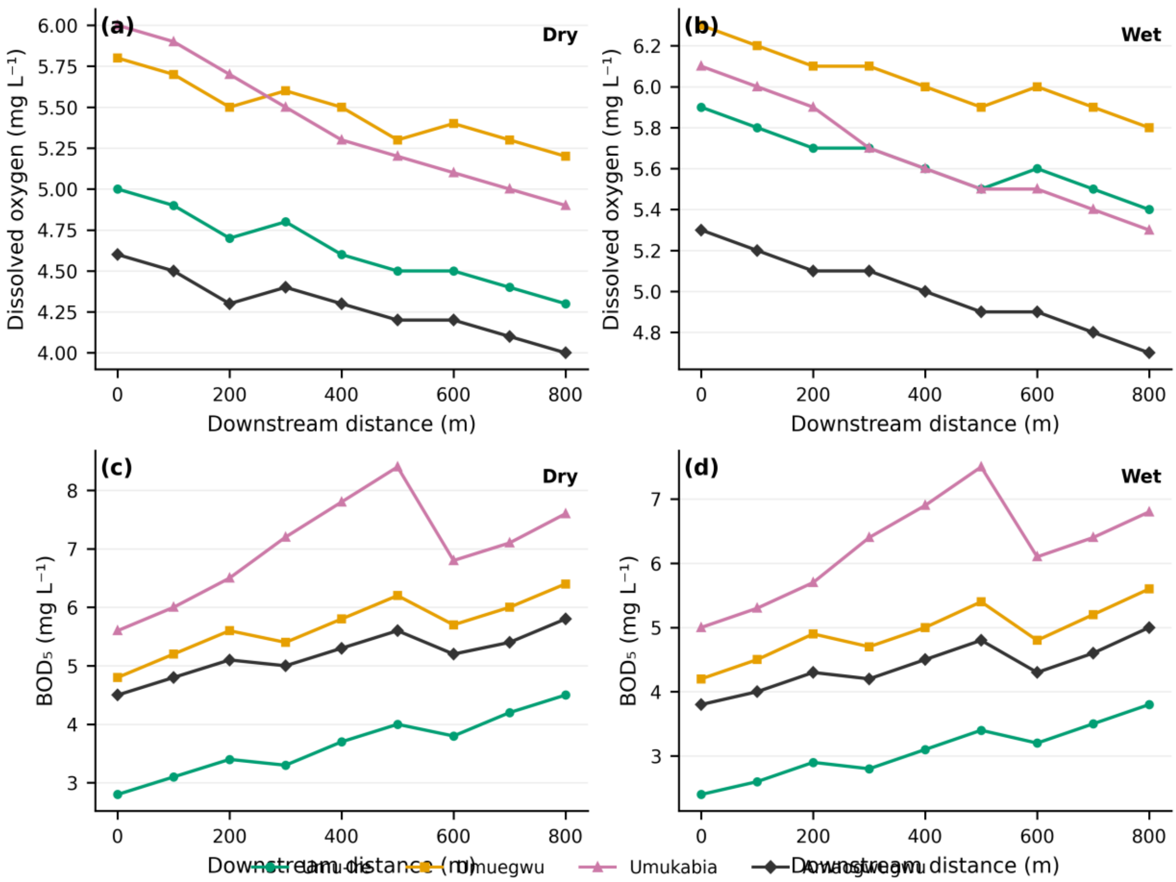

Figure 6: Longitudinal dissolved oxygen and BOD_5 profiles by reach and season

3.3 Hydro-sediment coupling, dilution and paired seasonal effects

Raw scatterplots showed a strong positive relationship between discharge and TSS and between TSS and turbidity (Figure 7). These relationships are consistent with increased transport capacity and the optical effect of suspended particles. The turbidity-TSS relationship was not perfectly linear because particle size, mineral composition, colour and organic matter influence light scattering; recent event-scale research similarly demonstrates that turbidity-SSC relations can change during complex rainfall hydrographs (Lu *et al*., 2024). Local suspended-solids measurements therefore provide the appropriate calibration basis for interpreting turbidity in Ikwu Stream.

Conductivity and TDS showed weaker pooled relationships with discharge (Figure 8), partly because reach-specific chemistry overlaid the seasonal dilution signal. Alkalinity and BOD_5 displayed a positive pooled association, suggesting that the more organically affected records also tended to have greater buffering or mineral influence. This does not mean that alkalinity causes BOD_5. Both may respond to common catchment inputs, wastewater pathways, decomposition and water-rock interaction. The hydro-chemical study from southern Nigeria reported that seasonal chemistry can reflect both weathering and human activity, reinforcing the need for cautious source attribution (Ubuoh *et al*., 2024).

The matched $\log_2$ response ratios in Figure 9 place variables on a common multiplicative scale. Discharge had the largest positive shift (mean $\log_2$ ratio 1.55), followed by TSS (0.68). DO and turbidity increased modestly, while temperature, conductivity, alkalinity and BOD_5 decreased. All bootstrap intervals excluded zero because the effect was consistent across the matched spatial records. Nevertheless, the intervals describe spatial consistency within the two campaigns, not repeatability across years. The result is strongest as an engineering statement: the wet-season operating envelope simultaneously involves greater available flow and greater solids loading.

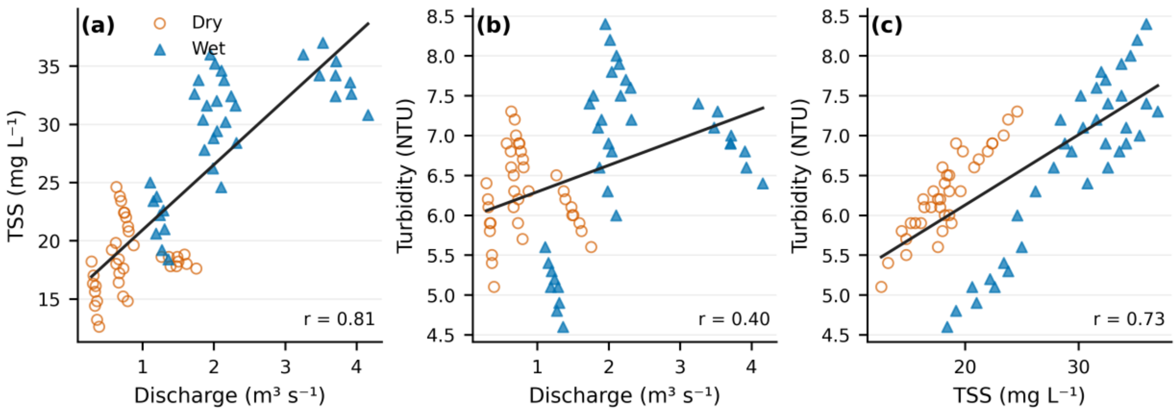

Figure 7: Descriptive pooled relationships among discharge, TSS and turbidity; lines are ordinary least-squares fits and r values are unadjusted Pearson coefficients

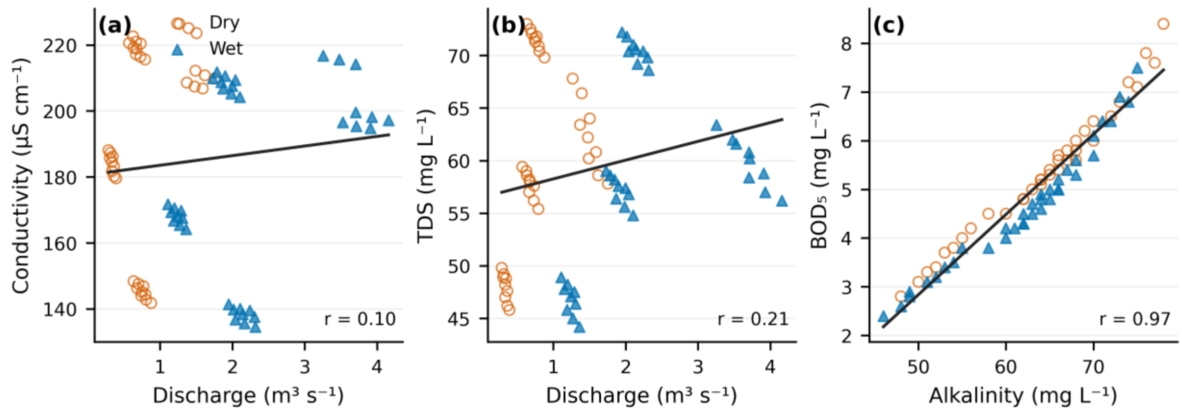

Figure 8: Descriptive pooled relationships for discharge-conductivity, discharge-TDS and alkalinity-BOD_5; lines are ordinary least-squares fits

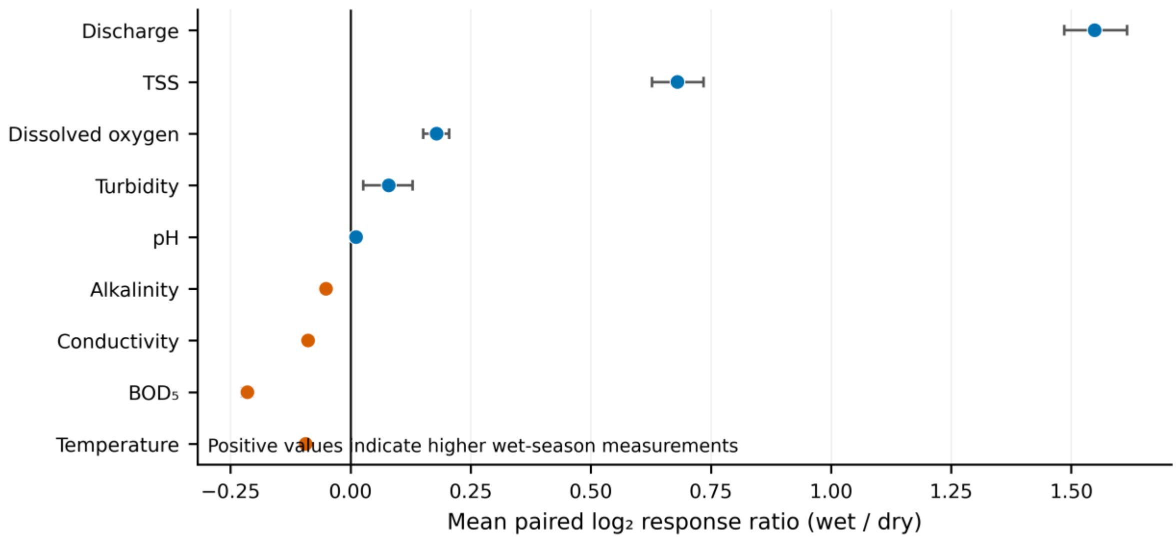

Figure 9: Mean paired $\log_2$ response ratios for wet versus dry conditions with bootstrap 95% confidence intervals

3.4 Covariate-adjusted relationships and process interpretation

Adjustment for season, reach, lateral position and downstream distance separated three coherent process groups (Table 5; Figure 10). First, alkalinity and BOD_5 remained strongly positively associated ($r = 0.872$, $q < 0.001$), indicating an organic-mineral or buffering signature that could not be explained solely by the fixed design factors. Second, discharge remained positively related to TSS ($r = 0.772$) and turbidity ($r = 0.660$), while turbidity and TSS were strongly coupled ($r = 0.775$). This persistence after adjustment strengthens the interpretation that the sediment signal was not merely a between-season artefact.

Third, DO was inversely related to turbidity ($r = -0.615$) and TSS ($r = -0.384$), while pH was positively associated with DO and negatively associated with the two particulate indicators. These relationships may reflect a combination of local organic demand, light attenuation, sediment-associated oxygen consumption and reach-scale hydraulic differences not fully captured by the fixed effects. They should not be read as mechanistic coefficients. The value of the adjusted matrix is that it identifies relationships deserving process measurements, such as event-based suspended-sediment sampling, sediment oxygen-demand tests and microbial analyses.

Conductivity showed no strong adjusted relationship with discharge, supporting the conclusion that ionic variation was structured mainly by reach chemistry and local inputs rather than a simple dilution gradient. This is important for source-water management: a single high-flow sample can obscure persistent reach-specific chemical characteristics. Routine monitoring should therefore preserve both seasonal and spatial coverage rather than replacing fixed stations with opportunistic sampling.

Table 5: Strongest covariate-adjusted Pearson correlations

Variable pair	**Adjusted r**	**FDR q**	**Direction**
Alkalinity-BOD_5	0.872	<0.001	Positive
Turbidity-TSS	0.775	<0.001	Positive
Discharge-TSS	0.772	<0.001	Positive
Discharge-turbidity	0.660	<0.001	Positive
pH-DO	0.632	<0.001	Positive
DO-turbidity	-0.615	<0.001	Negative
pH-turbidity	-0.491	<0.001	Negative
pH-TSS	-0.478	<0.001	Negative
Temperature-discharge	0.443	0.001	Positive
Temperature-DO	0.418	0.001	Positive
DO-TSS	-0.384	0.003	Negative
Alkalinity-TSS	0.366	0.005	Positive

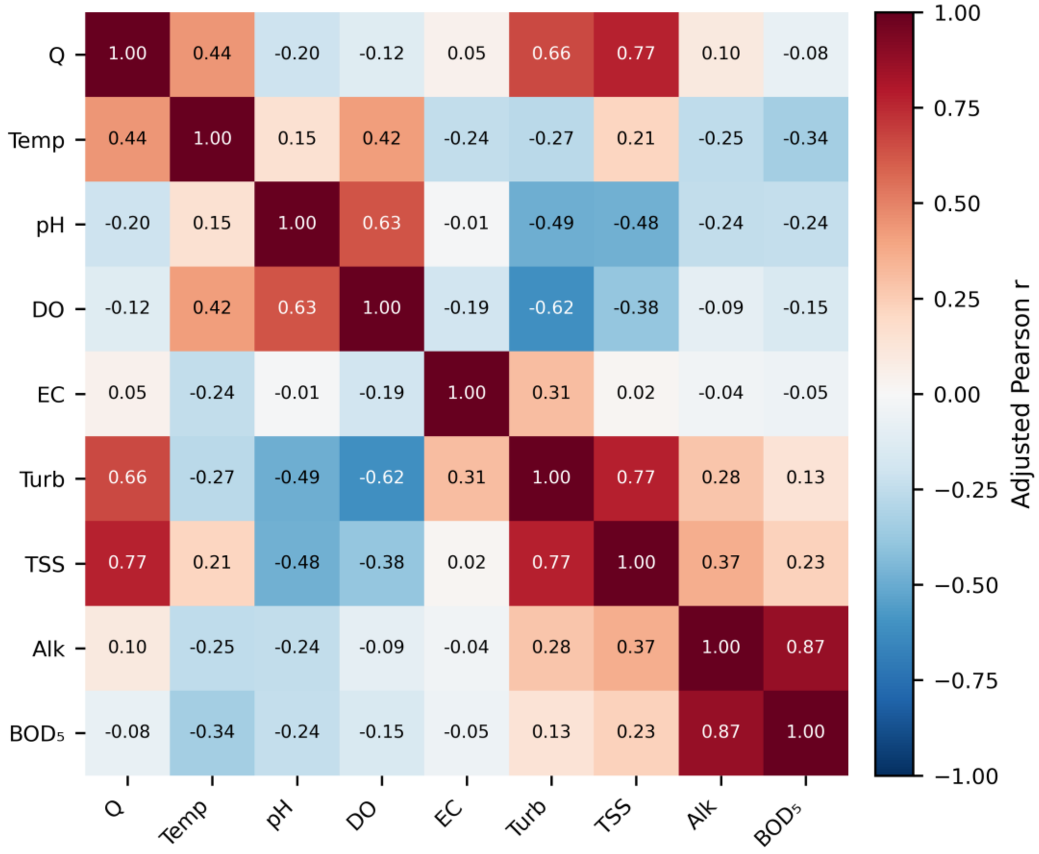

Figure 10: Pearson correlation matrix after adjustment for season, reach, lateral position and downstream distance

3.5 Principal component structure and integrated diagnosis

The biplot in Figure 11 separated low-flow dry observations from high-flow wet observations while retaining reach-specific clustering. Umukabia projected toward the organic-loading direction, whereas wet-season records projected more strongly toward discharge and TSS. This pattern independently supports the conclusions from the seasonal summaries and adjusted correlations: the study area is governed by at least two partially independent source-water stresses, one associated with organic/mineral influence and the other with rainfall-driven sediment transport.

The first three principal components explained 32.7%, 32.1% and 22.1% of the standardised variance, respectively; the first two accounted for 64.8% and the first three for 86.9% (Figure 12a). The corresponding loading structure (Figure 12b) showed that PC1 was dominated by BOD_5 and alkalinity, representing an organic-mineral or wastewater-buffering signature; PC2 was dominated by discharge, TSS and turbidity, representing a hydrodynamic suspended-solids axis; and PC3 contributed additional separation associated with oxygen, pH and temperature.

PCA is useful here because it shows why a single water-quality index or a single "best season" designation would be misleading. A sample can have improved DO and lower BOD_5 while simultaneously experiencing greater particulate treatment demand. The engineering response should therefore be multi-objective: protect the upstream reach from organic inputs, control sediment mobilisation in the catchment and design treatment for the worst credible turbidity/solids envelope rather than the seasonal mean alone.

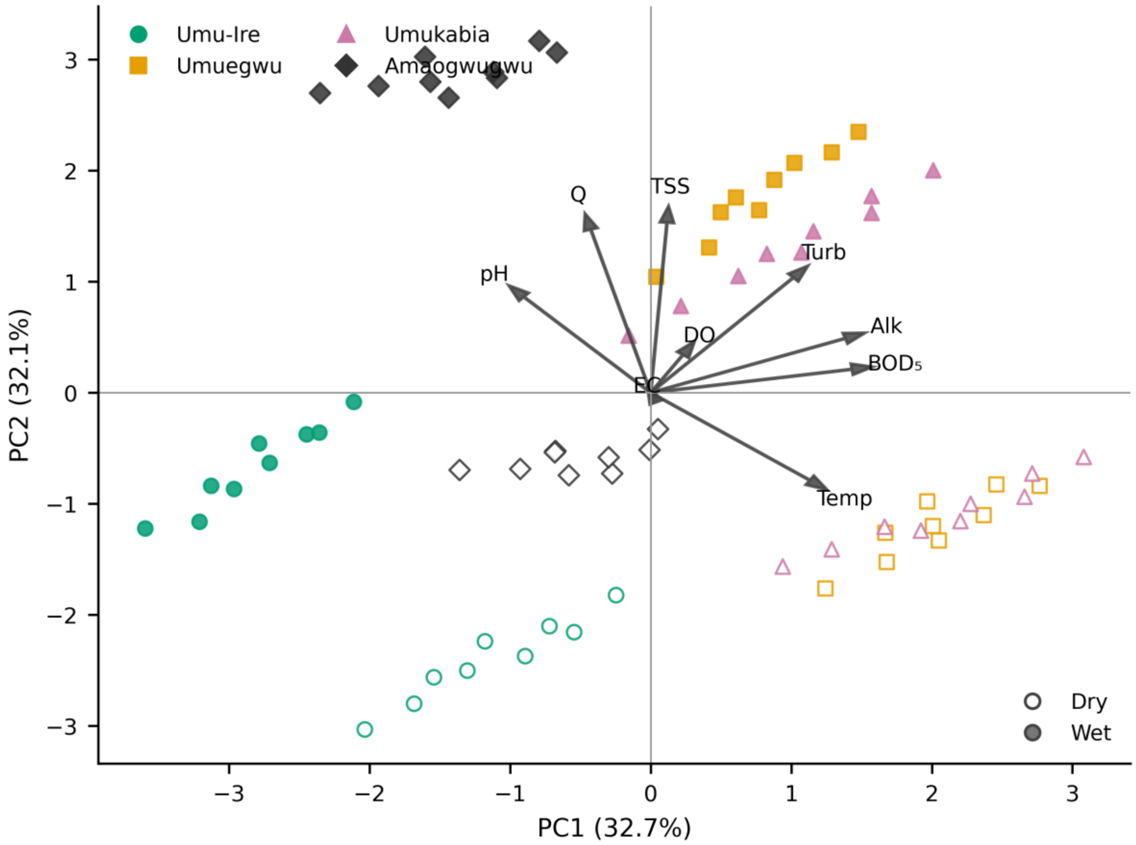

Figure 11: Principal component biplot for standardized hydrodynamic and water-quality variables; open symbols represent dry-season observations and filled symbols represent wet-season observations

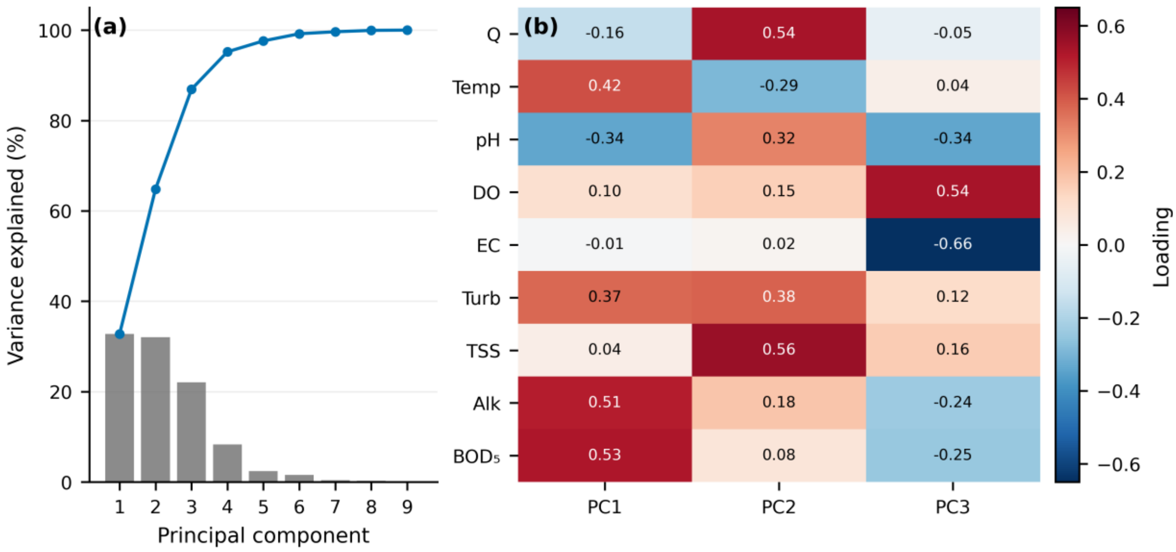

Figure 12: PCA diagnostics: explained and cumulative variance by component (a) and loadings for the first three principal components (b)

3.6 Abstraction, treatment and monitoring implications

Among the assessed reaches, Umu-Ire presented the most favourable physicochemical profile for detailed abstraction assessment because it combined the lowest BOD_5 with relatively low turbidity and adequate seasonal flow. This finding is restricted to the variables measured: comparatively low BOD_5 does not demonstrate the absence of E. coli, total coliforms or other microbial hazards, and the raw water is not suitable for untreated consumption. Detailed intake development requires topographic and flood assessment, repeated low-flow gauging, microbial and broader chemical screening, sanitary inspection and protection of the upstream buffer from washing, livestock access, waste discharge and sediment-generating disturbance.

The results define two seasonal operating envelopes. During dry low-flow conditions, monitoring priorities are BOD_5, DO, conductivity, evidence of local discharges and abstraction sustainability. During wet weather, the priorities shift to turbidity, TSS, colour, microbial indicators and rapid flow changes. Potable-water treatment requires intake screening, coagulation and flocculation, clarification, filtration, disinfection and protected storage, supported by jar testing and filter-run assessment on representative seasonal and storm-event raw water (Crittenden *et al*., 2012; World Health Organization, 2022, 2024). Turbidity control precedes disinfection because suspended particles can reduce disinfectant effectiveness.

The study is strengthened by its matched spatial design, complete data structure, georeferenced reach framework, transparent residual adjustment and reproducible figures. Its principal limitations are the absence of repeated seasonal campaigns, continuous stage and rainfall records, microbial and nutrient measurements, full laboratory precision records and event-based samples. The findings are transferable as a diagnostic framework for similar small tropical streams, whereas numerical design values require site-specific verification. Further investigation should include monthly monitoring across a complete hydrological year, targeted first-flush and peak-flow sampling, E. coli and total coliforms, nutrients, oil and grease, metals, pesticides and pilot-scale treatment tests.

4.0 CONCLUSION

Ikwu Stream exhibited a strong but non-uniform seasonal response. Wet-season discharge increased by 175.6%, DO increased by 12.8% and BOD_5 decreased by approximately 14%, indicating greater water availability, cooling, reaeration and partial dilution of organic loading. At the same time, TSS increased by 61.1% and turbidity remained above 5 NTU in almost all observations. The stream therefore cannot be described as simply cleaner in the wet season: oxygen condition improved while particulate treatment demand increased. Reach-scale analysis identified Umu-Ire as the lowest-BOD_5 location and the most defensible candidate for detailed abstraction assessment, whereas Umukabia retained the strongest organic-loading signature. This ranking is physicochemical only: low BOD_5 at Umu-Ire does not guarantee microbial safety or justify untreated drinking-water use. Design-adjusted correlations and PCA resolved two dominant process groups-an organic-mineral axis represented by BOD_5 and alkalinity, and a hydrodynamic suspended-solids axis represented by discharge, TSS and turbidity. These independent lines of evidence support an upstream-first abstraction strategy, catchment sediment and waste controls, season-specific monitoring and a multi-barrier treatment train. The conclusion is deliberately bounded: potable-water suitability requires microbial and broader chemical testing, repeated hydrological monitoring and pilot treatment verification. The reproducible dataset and code provide a transparent foundation for those next steps and for comparative assessment of other community-scale tropical stream sources.

DECLARATIONS

Ethics approval and consent to participate:

Not applicable. The manuscript reports physicochemical measurements of environmental water and does not include human or animal subjects.

Availability of data and materials:

The experimental dataset supporting the findings is included in the manuscript tables. Raw instrument output files, Python scripts and laboratory notebooks are supplied as supplementary materials.

CRediT authorship contribution statement

All authors contributed immensely to every stage of this research including: study conceptualization, carrying out the laboratory works, reporting, modelling and conclusion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Consent for publication:

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